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Discussions

Morphological characteristics and conditions of drainage basins contributing to the formation of debris flow fans: examination of regions with different rock strength using decision tree analysis

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Abstract. Debris flows cause severe disasters, such as human damage and the collapse of houses. Establishment of the early warning systems in the basins with high debris flow risks is needed to reduce debris flow disasters. Because debris flows often form debris flow fans near the mouths of valleys, debris flow fans are regarded as important topographical elements that indicate the occurrence of debris flows. The presence or absence of a debris flow fan makes it possible to clarify the morphological conditions of the contributing area that has generated debris flows. These morphological conditions may depend on the rock strength, which controls weathering activity and grain size of sediments. In this study, we investigated the morphological conditions of a drainage basin that contribute to the formation of debris flow fans using decision tree analysis. The analysis was conducted at two sites with clearly differences in rock strength due to geological sedimentation processes: Neogene sedimentary rocks and Paleogene accretionary prism sites. As a result of decision tree analysis using data sets of total 158 basins, the thresholds of morphological parameters needed for forming debris flow fans differed depending on the geological features. In the Paleogene accretionary prism site, when the relief ratio was less than 0.29, coarse-grained sediments were less likely to pass out from the valley, resulting in the absence of debris flow fans. On the other hand, in Neogene sedimentary rocks sites, short basins were determined to form debris flow fans, even if the relief ratio was less than 0.36 because the sediments were fine-grained and tended to flow downstream. In contrast, morphological factors that influence the presence or absence of debris flow fans were common at both sites. The first, second, and third most important morphological factors were the relief ratio, most frequent slope gradient, and basin length, respectively. Therefore, these morphological factors are considered important in evaluating debris flow risks. This study demonstrated that the decision tree analysis is an effective tool to obtain hierarchy and threshold of morphological factors that classifies the presence and absence of debris flows reaching valley mouths.

1 Introduction

Debris flows cause severe disasters, such as human damage, the collapse of houses, and floods owing to the large sediment volume, high kinematic energy, significant deposition of a large amount of sediments (Dowling and Santi, 2014; Badoux et al., 2016). Establishment of the early warning systems in the basins with high debris flow risks is needed to reduce debris flow disasters. Because debris flows often form debris flow fans near the mouths of incised valleys, debris flow fans are regarded as critical topographical elements that indicate the occurrence of debris flows (De Haas et al., 2015; De Haas et al., 2018). Therefore, the presence or absence of a debris flow fan makes it possible to clarify the topographic conditions of the contributing area that generated debris flows. These topographic conditions can be used to evaluate debris flow risks before conducting detailed field surveys.

Many studies have been conducted to clarify the relationship between the formation of alluvial fans and the morphological features of drainage basins (Guzzetti et al., 1997; De Scally and Owens, 2004). Other studies have classified debris flow basins and debris flood basins based on the morphological features of the drainage basin and alluvial fan (Wilford et al., 2004; Ilinca, 2021).

Morphological factors of the drainage basin affecting alluvial fan formation include the basin area, maximum basin length, basin relief, slope gradient, and relief ratio in the maximum catchment length direction (Meyer and Wells, 1997; De Scally and Owens, 2004; Wilford et al., 2004; Rowbotham et al., 2005; Zhou et al., 2016). Basin area is a factor that affects sediment supply activity (De Scally and Owens, 2004). There is a positive correlation between the basin and alluvial fan areas (Melton, 1965; Guzzetti et al., 1997; Giles, 2010; Benvenuti et al., 2016) and a strong negative correlation between the basin area and alluvial fan gradient (Gómez-Villar and García-Ruiz, 2000; Crosta and Frattini, 2004; De Scally and Owens, 2004; De Haas et al., 2015). Debris flows terminate before the valley mouth more easily if the maximum basin length above the valley mouth is greater (Wilford et al., 2004). The amount of uplift affects the basin relief; erosion and sediment supply are more active in basins with higher basin relief (Zhou et al., 2016). The slope gradient describes the steepness of the overall slope in the basin and is a factor controlling sediment supply activity (Rowbotham et al., 2005). The relief ratio, the channel gradient along the direction of maximum basin length, represents morphological conditions that promote sediment supply and control the sediment delivery ratio to the outside of the valley (Meyer and Wells, 1997).

The morphological features of the drainage basin have also been used to determine the types of sediment transfer forming alluvial fans (Crosta and Frattini, 2004; Wildford et al., 2004; De Scally et al., 2010; Ilinca, 2021). For example, Wildford et al. (2004) reported that debris flow and debris flood could be effectively discriminated from a combination of the Melton ratio (basin relief divided by the square root of the basin area) and basin length. In addition, De Scally et al. (2010) pointed out that the ruggedness of the basin (Melton ratio and relief ratio along the maximum catchment length direction) and alluvial fan gradient (e.g., the gradient in the upper part and average gradient) are important morphological factors for distinguishing between debris flows and debris floods. However, the thresholds dividing the two processes differ depending on the geology (De Scally et al., 2010; Ilinca, 2021). Crosta and Frattini (2004) also classified debris flows and debris floods based on morphological conditions in the drainage basin using the discriminant function and logistic regression analysis. They reported that some debris flood basins were misclassified as debris flow basins owing to the differences of the erodibility on the bedrock. In other words, the dominant types of sediment movement process differ depending on the difference in geology. Therefore, it is necessary to clarify the morphological conditions of debris flow occurrence in each geological setting. However, the importance and threshold of morphological factors within drainage basins in forming debris flow fans have only been investigated in a few regions (Crosta and Frattini., 2004; De Scally et al., 2010; Ilinca, 2021). In addition, the commonalities among different geologies have not yet been sufficiently clarified. These are important for improving the accuracy of debris flow risk evaluation.

In recent years, various machine-learning analyses have been performed to clarify the factors that cause natural disasters. Decision tree analysis is machine learning that uses a tree structure to explain the estimation procedure and order of important explanatory variables from a large dataset (Witten and Frank, 2005). Therefore, it is useful to clarify the morphological conditions contributing to debris flows and landslides (e.g., Saito et al., 2009; Zhang et al., 2019). If the presence or absence of debris flow fans and morphological factors of the drainage basin are used as the objective and explanatory variables, respectively, it is possible to reveal the morphological conditions contributing to the formation of debris flow fans in each geology. Furthermore, considering the morphological conditions of the drainage basin forming debris flow fans as the conditions generating debris flows, the risk of debris flow occurrence can be evaluated even in basins where debris flow fans are not identified owing to the effects of erosion by mainstream rivers and artificial land formation.

The purpose of this study is to clarify the morphological conditions of basins that contribute to the formation of debris flow fans in sites with different geology. In this study, we selected the Neogene sedimentary rocks and the Paleogene accretionary prism sites in Hokkaido, northern Japan, which have significantly different rock strength due to geological sedimentary processes. In addition, based on decision tree analysis and field surveys, we clarified the commonalities and differences in morphological conditions that affect the formation of debris flow fans due to differences in the rock strength. Because many debris flow fans have been formed without significant artificial modification in the study sites, it is easy to evaluate the differences in the formation conditions of the debris flow fan between the two geological properties. We have selected decision tree analysis because it can objectively provide hierarchy and threshold of morphological factors that classify the presence and absence of debris flow fans.

2 Study sites

The study sites were located in the southeastern and western parts of the Hidaka Mountains in Hokkaido, northern Japan (Fig. 1a). The geology of the study sites consists of two geologies: Neogene sedimentary rocks in the western site with an area of 161 km^2 (Fig. 1b), and a Paleogene accretionary prism in the southeastern site with an area of 59 km^2 (Fig. 1c). The geological settings at the study sites were assessed using the 1:200,000 seamless digital geological map v2 (Geological Survey

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of Japan, 2022). Climate conditions may not clearly affect differences in sediment transfer processes between the two sites because they are located in the same region.

The Paleogene accretionary prism site located southeast of the Hidaka Mountains corresponds to the Nakanogawa group (coherent facies) (Nanayama, 1992) and is mainly composed of sandstone and slate (Suzuki et al., 1959). In contrast, the Neogene sedimentary rocks in the western study site consist mainly of diatomaceous siltstone, sandstone, and conglomerate of the Nina Formation (Imai and Sumi, 1957). According to field surveys, the rocks of the western study area (Neogene sedimentary rocks site) were underlain by soft rocks highly slaked by weathering. On the other hand, the rocks of the southeastern study area (the Paleogene accretionary prism site) were found to be hard rocks without progress of weathering. Unconfined compressive strength of Neogene sedimentary rocks in Japan is approximately 0.49-19.6 (MPa), while that of Paleogene sedimentary rocks is generally higher than 19.6 (MPa) (Japan Society of Civil Engineers, 1987). Although rock strength varies even in the same geological unit due to differences in accretion and metamorphic grade (Moore and Saffer, 2001), rock strength in Paleogene accretionary prism site tend to be higher than that in Neogene sedimentary rocks site. In addition, based on the field survey of slope failures, the grain size of the deposits from slope failures in the Neogene sedimentary rocks site was much finer than that in the Paleogene accretionary prism site.

In the Paleogene accretionary prism site, three large rivers (Nishihiroo, Nakahiroo, and Higashihiroo) flow down from the southwest to the northeast (Fig. 1c). Small valleys of tributaries (hereafter drainage basins) with areas of 0.83 to 122 ha, which were the study sites, are arranged along these rivers. At the Neogene sedimentary rocks site, the Hae and Hidakamonbetsu Rivers flow down from the northeast to the southwest (Fig. 1b). Drainage basins with areas of 1.2 to 211 ha, which were also the study sites, are arranged along the two rivers. At both study sites, there were many valleys with and without debris flow fans at their mouths.

The Paleogene accretionary prism site has a steeper topography than the Neogene sedimentary rocks site (Figs. 1b, 1c, 2a). The minimum slope gradient of the Paleogene accretionary prism site approximately corresponds to the median slope gradient of the Neogene sedimentary rocks site (Fig. 2a). The basin reliefs of the Paleogene accretionary prism site were often larger than those of the Neogene sedimentary rocks site (Fig. 2b). In addition, the basin relief ranges from small to large, and the variation is greater than that at the Neogene sedimentary rocks site (Fig. 2b). Many of the relief ratios at the Paleogene accretionary prism sites are larger than those at the Neogene sedimentary rocks sites (Fig. 2c). In addition, the relief ratio ranged from small to large, and the variation was greater than that at the Neogene sedimentary rocks site (Fig. 2c). Furthermore, the slope gradient maps show that gentle slopes, which are not affected by incision by channel networks, are more widely distributed in the Neogene sedimentary rocks site than in the Paleogene accretionary prism site (Figs. 1b, 1c). Although rock strength would have a large variation even in a same geology, differences in the topographic features between the two study sites indicate that the rock strength is significantly different the two sites.

The uplifting rate in the Late Quaternary in Paleogene accretionary prism site (0.1 mm year^{-1}) is lower than that in the Neogene sedimentary rocks site (0.5 mm year^{-1}) (Yoshiyama, 1990).

don't use one sentence paragraphs - try to combine with previous paragraph or expand this one.

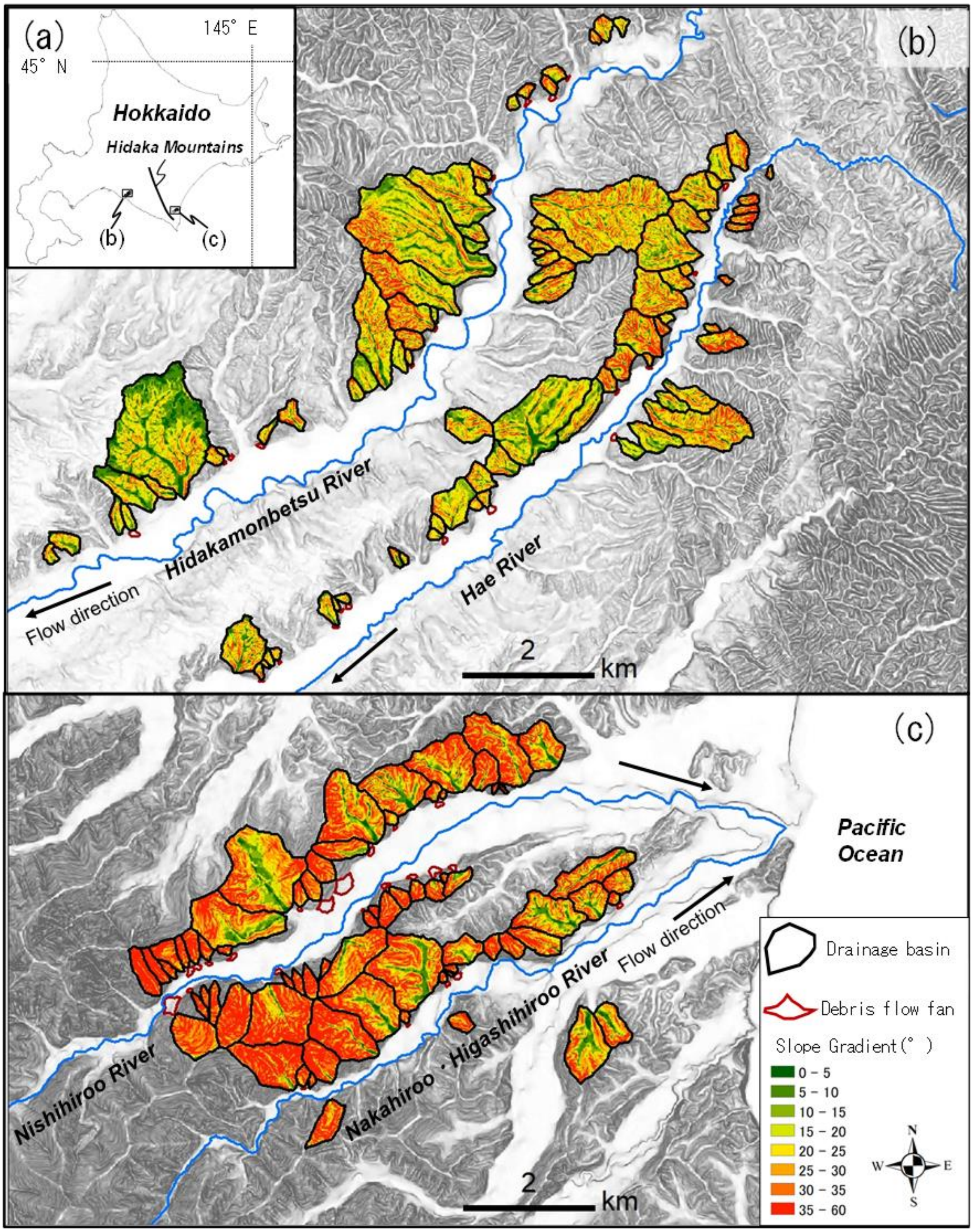

Figure 1: Map of the study sites: (a) location of study sites is in black areas. (b) Slope gradient of drainage basins in the Neogene sedimentary rocks site. (c) Slope gradient of drainage basins in the Paleogene accretionary prism site. Darker areas in the background indicate steeper topography.

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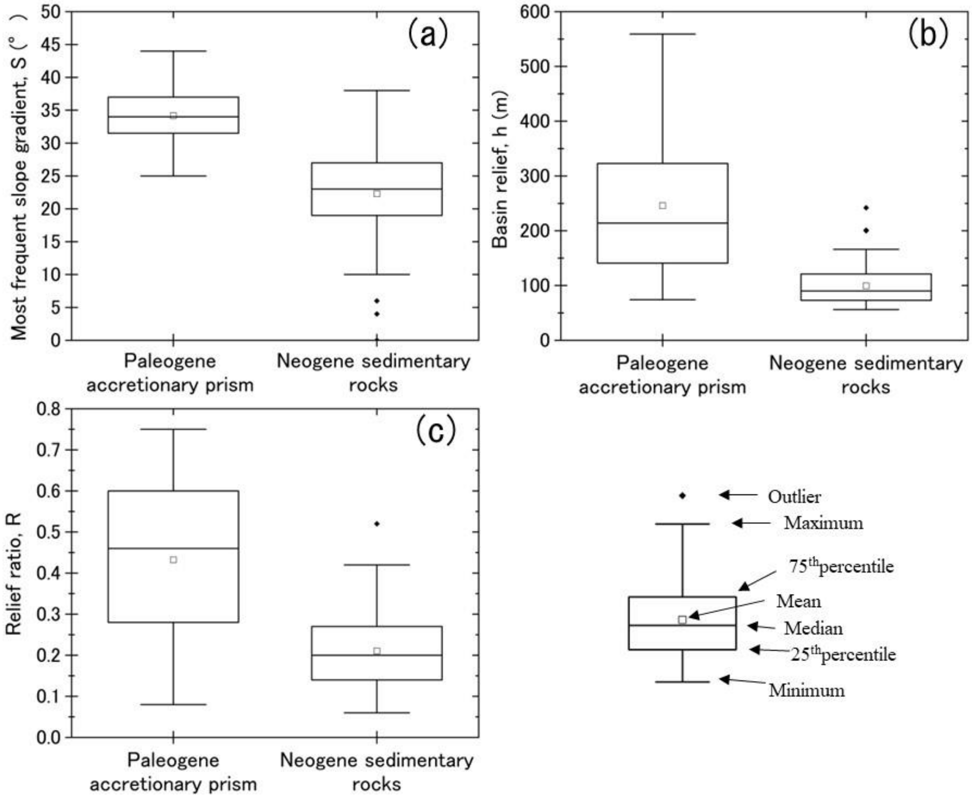

Figure 2: Topography of each drainage basin in the Paleogene accretionary prism site and the Neogene sedimentary rocks site: (a) most frequent slope gradient, (b) basin relief, (c) relief ratio.

3 Methodology

GIS and decision tree analyses were performed according to the flowchart shown in Fig. 3. First, debris flow fans and the boundaries of drainage basins at the study sites were extracted using topographic maps and DEMs. After calculating the morphological parameters in each basin, a decision tree analysis was performed using the presence or absence of debris flow fans as the objective variable and the morphological variables of the drainage basin as the explanatory variables. The morphological properties of the drainage basins were calculated using ArcGIS 10.8 (Esri Inc.). DEMs with a grid size of 10 m built from the topographic map of the Geospatial Information Authority of Japan (1:25000 topographic map) were used to calculate the morphological variables.

Field surveys were conducted in 18 and eight basins in the Paleogene accretionary prism site and Neogene sedimentary rocks site, respectively, to validate the extraction of debris flow fans from topographic maps. The characteristics of the basins, such as grain size, timing of debris flows, and morphology of debris flow fans, were also assessed by field surveys.

Maybe state when these surveys were conducted

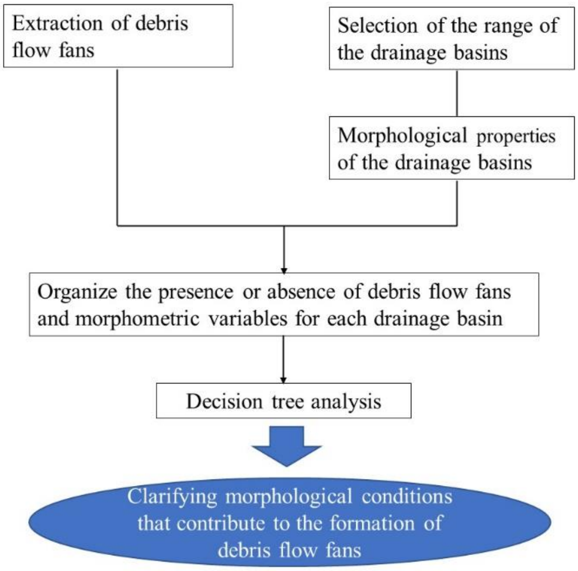

Figure 3: Flow chart of the analysis.

3.1 Selection of the range of the drainage basins

The boundary of the drainage basins at each study site was automatically extracted from 10 m grid DEMs using the Spatial Analyst tool of ArcGIS 10.8. The lower end of the drainage basins was set at the valley mouth, where the narrow valley-shaped topography formed by tributaries changes to a wide and flat terrain affected by fluvial processes of the main rivers. The basin boundaries automatically extracted from the DEMs were checked by overlapping with 1:25000 topographic maps of the Geospatial Information Authority of Japan using GIS software. Basins with an area of 8,000 m^2 or less have a topography that resembles a hillslope more than a watershed. In addition, many of these small basins have talus slopes, rather than debris flow fans, in their lower parts. Hence, the lower limit of the basin area analyzed in this study was set to 8,000 m^2.

OK, but please note that watersheds can be any size

3.2 Extraction of debris flow fans

Because this study focuses on debris flow fans, fan-shaped sedimentary landforms near the valley mouth, which have a slope gradient similar to common debris flow fans, were extracted from 1:25000 topographic maps using GIS. De Haas et al. (2018) found that the slope gradients of debris flow fans determined by field observations are often greater than 5°. Takase et al. (2002) reported that the slope gradient of debris flow fans in Japan generally ranges from 5° to 22°. Fan-shaped topography gentler than this gradient range is likely affected by debris flooding, whereas topography steeper than this range is possibly a talus cone. For this reason, we extracted fan-shaped sedimentary topographies, which have a main-axis gradient of 5–22°, as debris flow fans. It was difficult to extract small-scale debris flow fans with a relative height of less than the contour interval (10 m) in this analysis. Hence, we analyzed debris flow fans exceeding 10 m.

3.3 Morphological variables of the drainage basin

Six morphological properties in drainage basins that potentially contribute to the formation of debris flow fans were selected based on previous studies (Meyer and Wells, 1997; De Scally and Owens, 2004; Wilford et al., 2004; Rowbotham et al., 2005; Zhou et al., 2016) and field surveys. The six selected morphological properties were: (1) basin area, (2) basin length, (3) basin relief, (4) most frequent slope gradient (hereafter MFSG), (5) relief ratio, and (6) channel gradient within 100 m upstream from the valley mouth (hereafter channel gradient) (Fig. 4). The properties were calculated from the 10 m grid DEMs using ArcGIS 10.8.

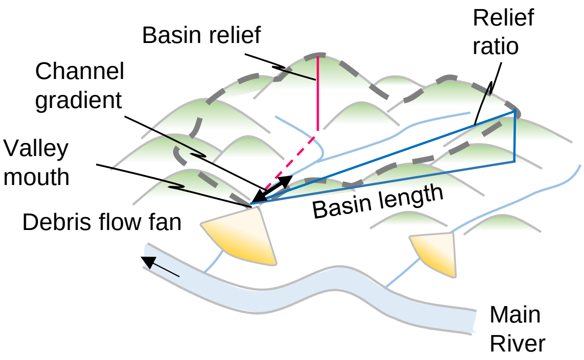

Figure 4: Conceptual figure of the six morphological characteristics.

The basin area was calculated using a geometric calculation tool in ArcGIS. The basin length was defined as the straight horizontal distance from the valley mouth to the furthest point in the basin. The basin length was likely to be shorter than the actual distance because the curve of the channel was ignored. Basin relief was obtained from the difference between the highest and lowest elevations. The MFSG was the highest frequency of integer slope gradient classes with an interval of 5°, calculated using the zonal statistic tool of ArcGIS. In this study, the class "5 degrees" indicated the slope gradient range from 1 to 5°, whereas the class "10 degrees" indicated 6 to 10°. Because the analysis was performed with a 10 m grid, steep microtopography smaller than the grid size (e.g., landslide scarps and channel banks) was classified into the gentler gradient class. The relief ratio was calculated as the relative height divided by the maximum horizontal basin length. The relative height used in the calculation of the relief ratio was the difference in altitude between the highest and lowest points along the maximum basin length. The channel gradient above the valley mouth was the relative height from the valley mouth to 100 m upstream, divided by 100 m. We assume this channel gradient affected the sediment transfer type at the valley mouth. If the length of the section for calculating this channel gradient is shorter than 100 m, the influence of local topographies, such as step pools, becomes significant. In addition, if the length of the section was longer, the middle channel reaches of the valley were included in the calculation section for some small basins. Therefore, 100 m was considered appropriate for calculating the channel gradient. Because the width of streams is usually smaller than the grid size of DEMs (10 m), part of the calculated channel gradient may

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be affected by the valley-side slopes. Because the DEM was created from the 10 m interval contour lines, the maximum error in the elevation value used for calculating morphological properties was approximately 10 m.

3.4 Decision tree analysis

Decision tree analyses with the presence or absence of debris flow fans as the objective variable and the morphological properties of the drainage basin as the explanatory variable were conducted using Weka 3.9.5, an open-source data mining tool developed mainly by Waikato University (Witten and Frank, 2005; The University of Waikato, 2006). The J48 algorithm, a re-implementation of the C4.5 algorithm (Witten and Frank, 2005), was used to construct the tree structure. Based on the decision trees obtained in the Paleogene accretionary prism site and the Neogene sedimentary rocks site, we discuss the morphological conditions in the drainage basin that contribute to the formation of debris flow fans. Variables in the higher-order tree structure are considered more important (Pal and Mather, 2003; Witten and Frank, 2005; Bou Kheir et al., 2008; Schneevoigt et al., 2008).

In the topographic map analysis, it was impossible to determine whether debris flow fans were lost because of erosion by the main rivers. In addition, the minimum distance from the fan apex (the drainage basin mouth) to the fan toe of the debris flow fan in the study sites was approximately 50 m. Therefore, if the distance from the valley mouth to the main river is less than 50 m, erosion of the main rivers may affect the presence or absence of debris flow fans. For this reason, basins were excluded from the analysis if the distance from the valley mouth to the river was less than 50 m.

4 Results

Methods were well articulated

4.1 Paleogene accretionary prism site

4.1.1 Field survey

shouldn't these be colluvial fans?

Field surveys revealed almost no fan-shaped topography with a slope gradient of gentler than 5° (debris flood fans) near the drainage basin mouth, whereas many alluvial fans with a slope gradient steeper than 5° (debris flow fans) were found (Fig. 5a). Debris flow fans are primarily composed of stony debris flow deposits. Most debris flow fans and channel deposits in the valley were not covered by vegetation (Fig. 5b). Recent debris flow deposits, which were not fully covered by vegetation, were found on debris flow fans (Figs. 6a, 6b). Therefore, erosion and deposition of sediments by debris flows still occur repetitively. As a result of photographic analysis of the grain size within a 1 m grid on the debris flow deposits, more than 95% were composed of pebbles (maximum particle size of 24 cm), whereas particles finer than pebbles were poor. In many valleys, slope failures occur on rocky slopes with well-developed joints, which continue to be a source of sediment. Large gravel with a diameter exceeding 1 m was produced from these rocky slopes.

The presence or absence of debris flow fans estimated by topographic map analysis was demonstrated by field surveys in 14 basins (78% of 18 surveyed basins). All four basins wrongly classified by topographic map analysis were missing debris flow fans on the topographic maps but were identified by the field survey. Field surveys in these four basins revealed that fluvial processes partially eroded the debris flow fans.

Maybe give some insights into why these were wrongly classified

4.1.2 Decision tree analysis

A total of 68 drainage basins were extracted using the GIS analysis. As a result of the topographic map interpretation, the numbers of basins with and without debris flow fans were 26 and 42, respectively.

The decision tree was composed of three variables and four leaves (Fig. 7). The decision tree analysis successfully classified the presence or absence of debris flow fans in 53 basins (78% of the 68 analyzed basins). The results of the decision tree analysis differed from those of the topographic map interpretation in 15 basins (hereafter, incorrect basins).

The relief ratio was the most important morphological factor (top hierarchy factor). The first decision indicates that debris flow fans were not formed under the condition of a relief ratio ≤ 0.29 (16.1°) (Acc Group 1 in Fig. 7). In the basins of Acc Group 1, the channel above the valley mouth was gentler than that at 5°. Field surveys have clarified that debris flows terminate before reaching the valley mouth. The second most important morphological factor was MFSG. The second decision indicates that debris flow fans were formed under the conditions of relief ratio > 0.29 and MFSG ≤ 35° (Acc Group 2 in Fig. 7). Field surveys of the Acc Group 2 basins revealed that the channel deposits in these basins were poorly covered by vegetation (Fig. 5b). In addition, recent debris flow deposits have been identified in debris flow fans (Figs. 6a and 6b). According to the GIS analysis, the upper part of the basins with an MFSG ≤ 35° did not experience significant downward dissection. Ten of the 26 basins classified into Acc Group 2 were incorrect basins, and debris flow fans were not identified in the topographic maps. In these incorrect basins, the channel gradient above the valley mouth was less than 5°. The basin length was the third most important morphological factor (the lowest hierarchy factor). The third decision indicates that debris flow fans were formed under the conditions of a relief ratio > 0.29, MFSG > 35°, and basin length ≤ 570 m (Acc Group 3 in Fig. 7). The downward dissection was apparent in the upper part of the basins classified as Acc Group 3. Five basins in Acc Group 3 (15 basins in total) were incorrect basins in which debris flow fans were not identified in the topographic maps. The formation of a stream channel was presumed based on the shape of the contours around the fan apex of the incorrect basins. Field surveys have revealed that this was a debris flow fan eroded by fluvial processes. The fourth decision indicates that debris flow fans were not formed under the conditions of a relief ratio > 0.29, MFSG > 35°, and basin length > 570 m (Acc Group 4 in Fig. 7).

4.2 Neogene sedimentary rocks site

4.2.1 Field survey

Field surveys revealed that the number of fan-shaped topographies with a slope gradient of less than 5° in the Neogene sedimentary rocks site was larger than that of the Paleogene accretionary prism site. In many of these, field surveys found no micro-landforms, such as debris flow snouts or lateral levees. There were only a few gravels on the surfaces of the fans. Additionally, a stratified structure was identified in the cross-sectional plane of the fan in some basins. Therefore, these gentle

little gravel and boulders?

fan-shaped topographies were likely formed by fluvial processes such as bed load and suspended sediment. Unlike the Paleogene accretionary prism site, most riverbed sediments and debris flow fans were covered with vegetation. Recent erosion and deposition of sediments were not observed in the field surveys (Figs. 5c, 5d). As a result of photographic analysis of the grain size within a 1 m grid on the debris flow deposits, the Neogene sedimentary rocks site was finer than the Paleogene accretionary prism site; approximately 70% were pebbles (maximum particle size of 14 cm) and approximately 30% were gravel? granules, sands, and silts. Fine-grained sediments are produced from outcrops on valley walls strongly weathered in many basins.

The presence or absence of debris flow fans classified by topographic map analysis agreed with the field survey in seven out of eight surveyed basins. In a basin that did not agree with the classification, the field survey revealed that the alluvial fan was small and slightly gentler than 5°. Thus, this incorrectly classified fan will likely be a debris flood fan.

4.2.2 Decision tree analysis

Ninety drainage basins were extracted using GIS analysis. As a result of the topographic map interpretation, the numbers of basins with and without debris flow fans were 24 and 66, respectively. The decision tree was composed of four variables and five leaves (Fig. 8). The results of the decision tree analysis agreed with those of the topographic map analysis in 77 of the 90 analyzed basins (86%), whereas the remaining 13 basins were incorrect.

The relief ratio was the most important morphological factor (top hierarchy factor). The first decision indicates that debris flow fans were formed under the condition of a relief ratio > 0.36 (19.8°) (Sed Group 1 in Fig. 8). The second most important morphological factor was MFSG. The second decision indicates that debris flow fans were not formed under the conditions of relief ratio ≤ 0.36 and MFSG > 25° (Sed Group 2 in Fig. 8). Field surveys in the Sed Group 2 basins revealed that the channel deposits in the valley were covered with vegetation, indicating low sediment transfer activity in the channel. In addition, according to the GIS analysis of these basins, the areas with slope gradients > 25° were mainly located on the slopes in the lower part of the basin formed by significant downward dissection. The third most important morphological factor was the MFSG. The third decision indicates that debris flow fans were not formed under the conditions of relief ratio ≤ 0.36 and MSFG ≤ 15° (Sed Group 3 in Fig. 8). The fourth most important morphological factor (the lowest hierarchy factor) was basin length. The fourth decision indicates that debris flow fans were formed under the following conditions: basin relief ≤ 0.36, 15° < MFSG ≤ 25°, and basin length ≤ 550 m (Sed Group 4 in Fig. 8). The area with a slope gradient of 15–25°was located on the slope above the knick line. Nine of the 25 basins in Sed Group 4 were incorrect basins, and debris flow fans were not identified in the topographic maps. A fan-shaped topography with a slope gradient of < 5° was identified at the mouth of these basins. The fifth decision indicates that debris flow fans were not formed under the following conditions: relief ratio ≤ 0.36, 15° < MFSG ≤ 25°, and basin length > 550 m (Sed Group 5 in Fig. 8).

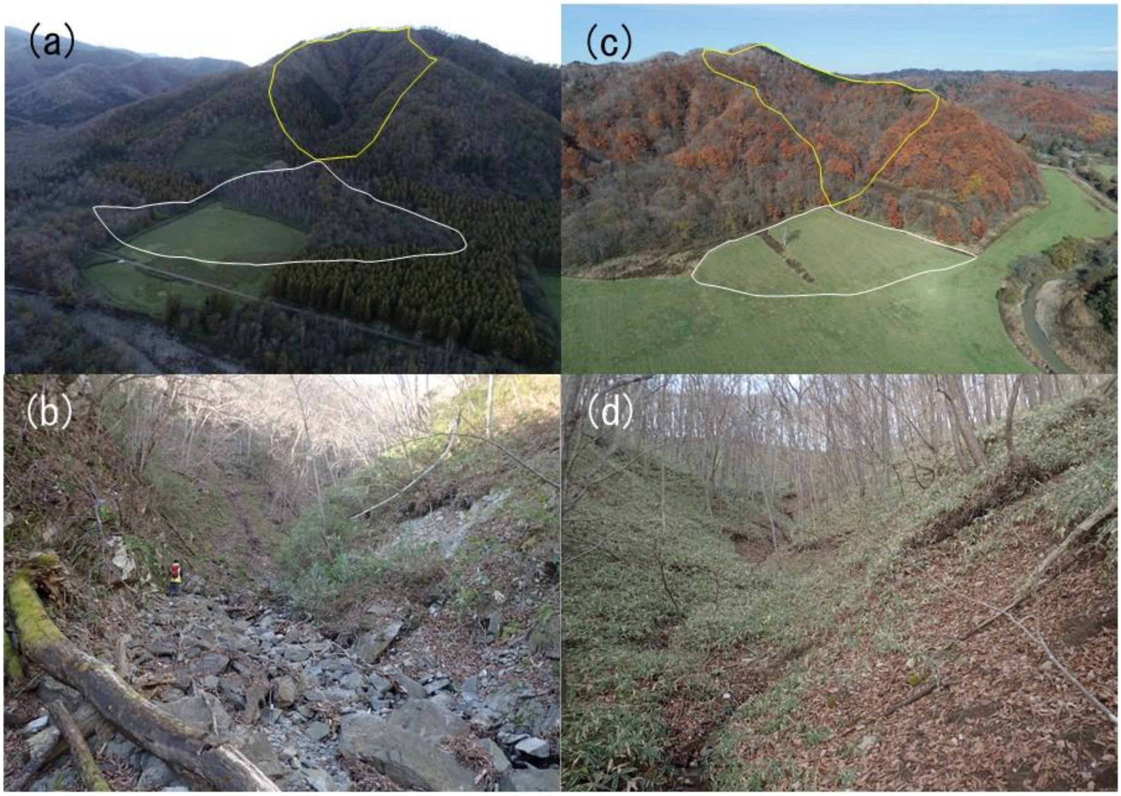

Figure 5: Debris flow fans and the channel of the drainage basins in both sites. (a) A debris flow fan in the Paleogene accretionary prism site. White and yellow solid lines are the debris flow fan and drainage basin boundaries, respectively. (b) Channel condition of the drainage basins in the Paleogene accretionary prism site. (c) A debris flow fan in the Neogene sedimentary rocks site. White and yellow solid lines are the debris flow fan and drainage basin boundaries, respectively. (d) Channel condition of the drainage basins in the Neogene sedimentary rocks site.

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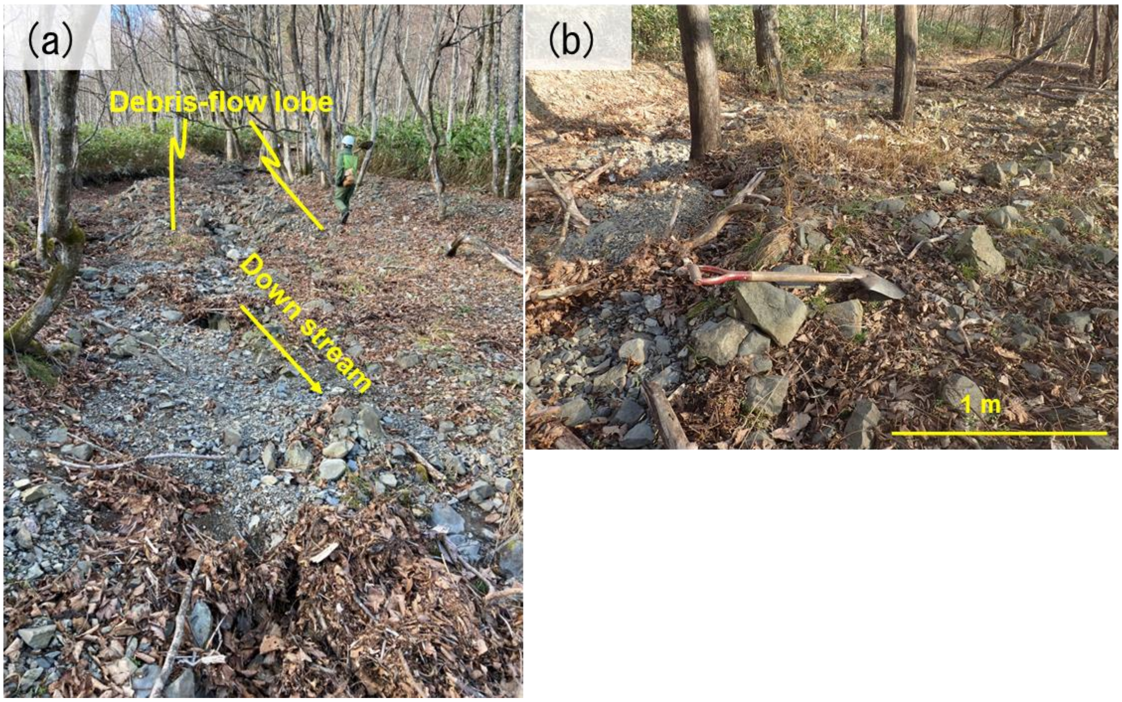

Figure 6: Recent debris flow deposits on debris flow fans of the Paleogene accretionary prism site: (a) debris-flow lobe, (b) boulders entrained by debris flows.

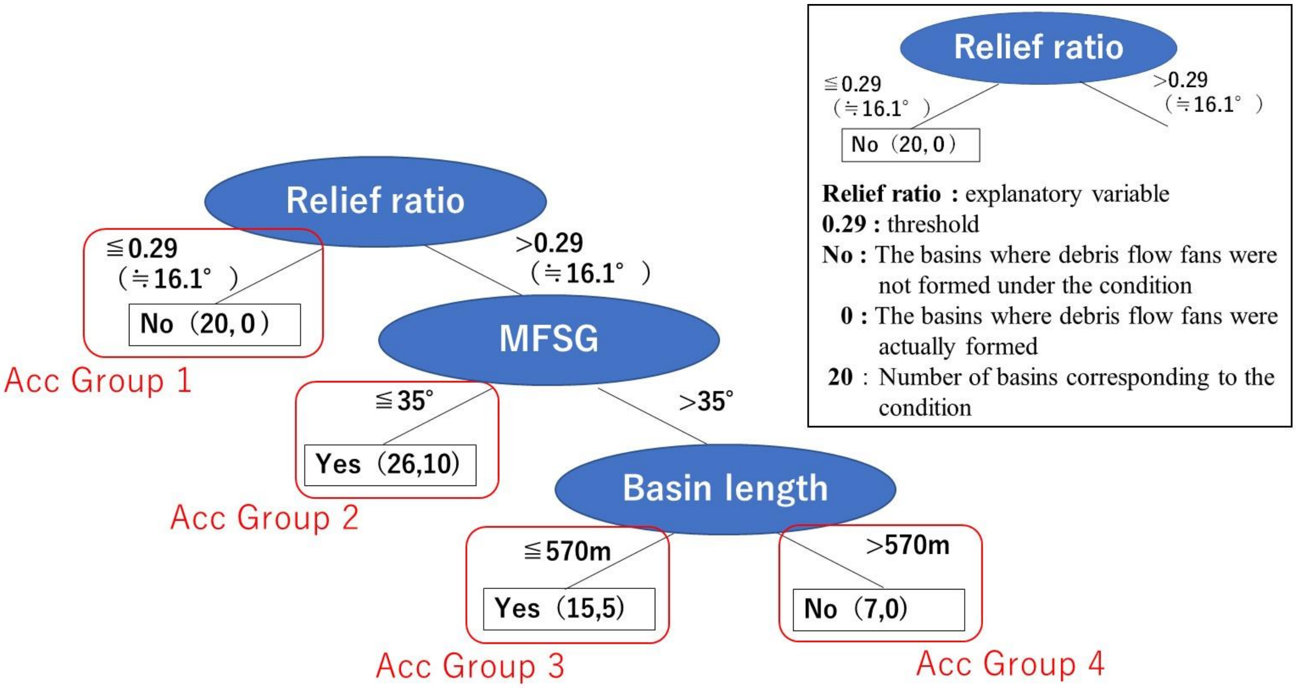

Figure 7: Decision tree for the Paleogene accretionary prism site.

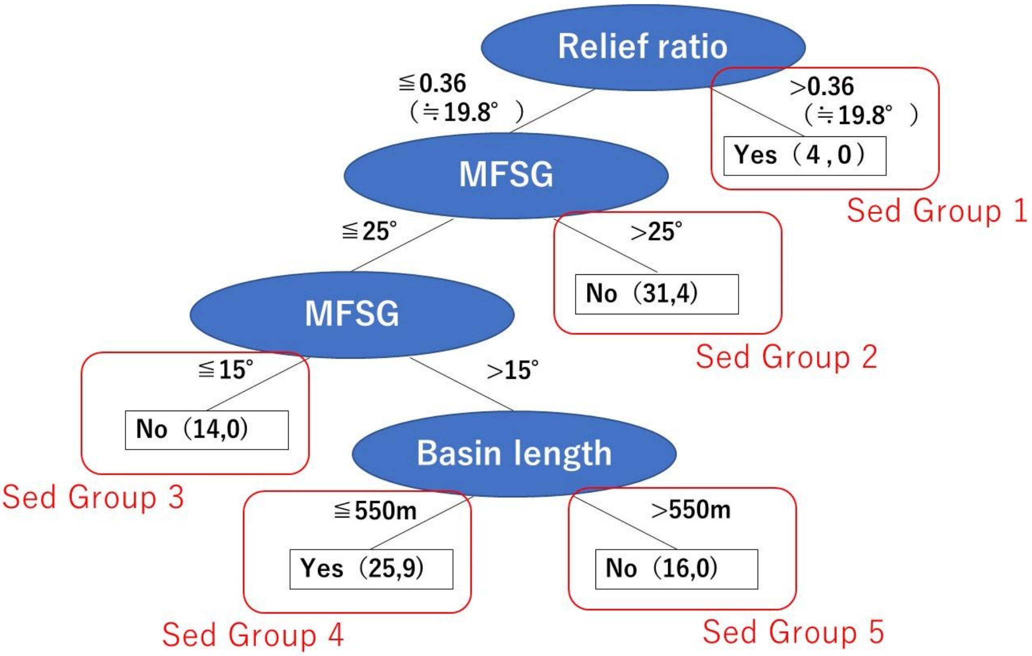

Figure 8: Decision tree for the Neogene sedimentary rocks site.

5 Discussion

5.1 Interpretation of drainage basins using decision tree analyses

5.1.1 Paleogene accretionary prism site

Debris flow fans were not formed in the Acc Group 1 basins, which had low relief ratios and gentle channels just above the valley mouth (Fig. 7). Debris flows are likely to terminate in the valley because debris flows terminate easily in gentle channel also Benda's research sections (Takaese et al., 2002; De Haas et al., 2018). In Acc Group 2, slopes gentler than 35° were distributed in the upper part of the basin, where downward dissection was not evident in the topography. A thick layer of weathered soil accumulates in areas where downward dissection has not yet progressed (Brosens et al., 2020). Therefore, thick regolith, a potential debris flow material, still exists on such gentle slopes, possibly facilitating the occurrence of debris flows. GIS analysis revealed that the channel gradient above the valley mouth in the incorrect basins in Acc Group 2 was less than 5°, suggesting that debris flow fans were not formed in these basins because of the termination of debris flows in the gentle channel sections (Takaese et al., 2002; De Haas et al., 2018). The Acc Group 3 basins had steep terrains (MFSG >35°) and short basin lengths (≤ 570 m). In the Acc Group 3 basins, unlike the Acc Group 2 basins, significant downward dissection has already reached upstream of the basin. Therefore, the remaining regolith, which can be debris flow material in the future, is limited. Jakob (2021) defined such basins as watershed supply-limited basins. However, because of the short length of the channel, once a debris flow occurs because of a landslide, it reaches the mouth of the basin. As a result, debris flow fans are formed in the Acc Group 3 basins. In the Acc Group 4 basins, landslide sediment did not reach the valley mouth as a debris flow because of the long basin length, resulting in missing debris flow fans (Calvace et al., 1997; Sorriso-Valvo et al., 1998; Gomez-Villar and Garcia-Ruiz, 2000; Crosta and Franttini, 2004). In addition, debris floods are more important than debris flows in basins with long basin lengths (Wildford et al., 2004; De Scally et al., 2010; Welsh and Davies, 2011).

5.1.2 Neogene sedimentary rocks site

Because the Sed Group 1 basins had a high relief ratio and a short basin length, the produced sediments easily reached the valley mouth as debris flows, forming debris flow fans. Previous studies have reported that the threshold of relief ratio needed for debris flow occurrence ranges from 0.25 to 0.37 (Wildford et al., 2004; De Scally et al., 2010; Ilinca, 2021). The results obtained in this study (0.36) were within the range of these thresholds.

The absence of debris flow fans in the Sed Group 2 and 3 basins was likely affected by the supply-limited characteristics of the basins (Bovis and Jakob, 1999; Jakob, 2021). In the Sed Group 2 basins, topography indicates past significant dissection unclear and poor remaining regoliths. In the Sed Group 3 basins, terrains are likely too gentle (MFSG ≤ 15°, relief ratio ≤ 0.36) to supply debris flow material to the channel. In the basin of Sed Group 4, the MFSG ranged from 15° to 25°, and slopes with such steepness were primarily distributed above the knick line. Therefore, hillslopes still store unstable sediments and are potential sources of debris flow material. In addition, because the basin length is short, the produced sediment easily reaches the outside of the basin as debris flows, forming debris flow fans. Gentle fluvial fans with slopes of less than 5° at the basin mouths were identified in the incorrect basins of Sed Group 4, indicating that fluvial processes evacuated the sediments. In Sed Group 5, debris flow fans were not formed because of the longer basin length than in Sed Group 4. As with the Paleogene accretionary prism site, landslide sediments were deposited in the valley and did not reach the valley mouth as debris flows. In addition, debris floods are more important sediment transfer process than debris flows in basins with longer basin lengths (Wildford et al., 2004; De Scally et al., 2010; Welsh and Davies, 2011).

5.2 Commonalities in morphological conditions contributing to debris flow fans formation

Decision trees of the Neogene sedimentary rocks (soft rock) site and the Paleogene accretionary prism (hard rock) site include the relief ratio, MFSG, and basin length (Figs. 7, 8). In addition, the hierarchy was in the order of relief ratio, MFSG, and basin length at both sites. Saito (1998) also pointed out that the relief ratio is the most important morphological factor affecting the presence or absence of alluvial fans. Wang et al. (2019) reported that the relief ratio is the most important morphological property for debris flow occurrence. Our decision tree analysis applied to 158 basins confirmed that the relief ratio is the most important factor in the formation of debris flow fans, regardless of the rock hardness. The relief ratio is a morphological factor that affects the sediment supply and evacuation from the valley (De Scally et al., 2010; Wang et al., 2019). Hence, the relief ratio is likely to be the most important factor controlling the formation of debris flow fans, regardless of geology. The MFSG and basin length are important factors affecting debris flow occurrence (Figs. 7, 8) (Rowbotham et al., 2005; De Scally et al., 2010). The MFSG likely affects regolith thickness (Brosens et al., 2020) and sediment supply activity, whereas the basin length controls the ratio of sediments reaching the valley mouth as debris flow. The threshold of basin length was not significantly different between the two geologies, and fewer debris flow fans were formed in basins with longer basin lengths. This trend is likely common regardless of geological settings, because similar trend has also been reported in other regions (e.g., Wildford et al., 2004; De Scally et al., 2010; Welsh and Davies, 2011).

debris fans?

Consequently, regardless of the geology, the morphological factors that control sediment supply activities and the ratio of sediments reaching the valley mouth as debris flow are closely related to the formation of debris flow fans.

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5.3 Differences in morphological conditions contributing to debris flow fans formation

Paleogene accretionary prism sites have higher bedrock strength, coarser-grain distribution of bed sediments, and higher relief ratio than Neogene sedimentary rocks sites (Fig. 2c). Relief ratio in harder rock basins is generally high because of low erodibility of valley side (Schmidt and Montgomery, 1995; Kühni and Pfiffner, 2001; Moore et al., 2009). Basins with coarser bed sediments have higher relief ratios and steeper channel gradients (Hack, 1957; Fratkin et al., 2020). In other words, the differences in geology affects rock strength and grain size of bed sediments, resulting in different relief ratio (Hack, 1957; Schmidt and Montgomery, 1995; Kühni and Pfiffner, 2001; Moore et al., 2009; Fratkin et al., 2020).

The threshold of morphological factors that classified the presence and absence of debris flow fans differed between the two geologies (Figs. 7 and 8). A debris flow fan was not formed at the Paleogene accretionary prism site when the relief ratio was 0.29 (16.1°) or less (Acc Group 1). The Paleogene accretionary prism site contained coarse-grained sediments. If the relief

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ratio is small, coarse sediments are not easily transported downstream, which makes it difficult to form debris flow fans. On the other hand, debris flow fans were formed in short basins in Neogene sedimentary rocks sites, even if the relief ratio was less than 0.36 (Sed Group 4). Sediments at Neogene sedimentary rocks sites are easily transported downstream because of their small size, even with low relief ratios. It has been reported that the lower limit of the relief ratio for forming debris flow fans differs depending on geology (Wildford et al., 2004; De Scally et al., 2010; Ilinca, 2021). De Scally et al. (2010) reported that the relief ratio in a Permian ultramafic intrusive rock area in the Southern Alps of New Zealand was 0.25. The threshold of the relief ratio is more than 0.30 in west central British Columbia, Canada, where granites, volcanic rocks, and sedimentary rocks are distributed (Wildford et al., 2004). Ilinca (2021) reported a threshold relief ratio of 0.37 or more in the Lotru watershed, central Southern Carpathians of Romania, where sandy marls, sandstones, and conglomerates (Late Cretaceous) are distributed. These results support our hypothesis that the smaller threshold of relief ratio in the Paleogene accretionary prism (hard rock) site than in the Neogene sedimentary rocks (soft rock) site is because of the smaller grain size in the former site. Therefore, it is considered that the difference in the relief ratio affects the threshold.

Next to the relief ratio, the most important morphological factor is the MFSG in both geological sites. However, the formation threshold of the debris flow fan in the Paleogene accretionary prism sites (35°) is higher than that in the Neogene sedimentary rocks site (15° to 25°; Figs 7, 8). Slope gradients of terrains that have not experienced significant dissection are less than 35° and 15° to 25° in the Paleogene accretionary prism and Neogene sedimentary rocks, respectively (Figs. 1, 2a). Such differences in the dominant gradients among geologies have also been reported by Korup (2008). Therefore, it is considered that the different thresholds of the MFSG between the two geologies are affected by the slope gradients of areas where significant dissection has not yet progressed.

6 Conclusions

In this study, we investigated the morphological conditions of a drainage basin that contribute to the formation of debris flow fans using decision tree analysis. The analysis was conducted at two sites with clearly differences in rock strength due to geological sedimentation processes: Neogene sedimentary rocks (soft rock) and Paleogene accretionary prism (hard rock) sites. As a result, important morphological factors affecting the presence or absence of debris flow fans were common regardless of geology. In both sites, the first, second, and third important morphological factors were the relief ratio, most frequent slope gradient, and basin length, respectively. These morphological factors are considered important in the evaluation of debris flow risks.

In contrast, the threshold of the morphological parameters needed for forming debris flow fans differed depending on the geological features. This might be due to the difference in physical properties of the two geological features. In other words, at the Paleogene accretionary prism site, when the relief ratio was less than 0.29, coarse-grained sediments were less likely to flow downstream, resulting in no formation of debris flow fans. On the other hand, short basins in Neogene sedimentary rocks sites were determined to have debris flow fans, even if the relief ratio was less than 0.36 because the sediments were fine-grained and tended to be transported downstream.

Field surveys and analyses of topographic map and DEM revealed that morphological conditions obtained by decision tree analysis control type and activity of sediment transfer processes in the study site. Therefore, this study demonstrated that the decision tree analysis is an effective tool to obtain hierarchy and threshold of morphological factors that classified the presence and absence of debris flows fans for each geology. The commonalities and differences in the morphological conditions for forming debris flow fans in different geologies could be clarified by the decision tree analysis. Morphological conditions for forming debris flow fans are essential in evaluating debris flow risks because the absence or presence of debris flow fans is highly affected by debris flow at the valley mouth. Therefore, it is possible that the morphological conditions obtained in this study can be used to assess debris flow risks in basins in which debris flow fans have been lost because of artificial land formation and fluvial processes. Furthermore, this study will be useful for designing an early warning system in basins with high risk of debris flow.

Would you also suggest that some checking of debris fan conditions in the field is important?

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